REAL TIME DIGITAL VIDEOMAGNETOGRAPH AT THE
AEROSPACE SAN FERNANDO SOLAR OBSERVATORY

CR-115113

1. Introduction

1.1 General types of magnetographs

Solar magnetographs using a spectrograph for spectral isolation and photomultiplier tubes as detectors have been in use since they were introduced in 1932 by Kuipenhauer and Babcock. Many refinements in recent magnetographs include Zeeman compensation (Evans), measurement of transverse magnetic fields, and use of multichannel detectors (Livingston).

A new approach was taken by Leighton in which film is used as the detector and two spectroheliograms are photographically subtracted. The instrument being described here uses a filter for spectral isolation and a television camera for sensor.

1.2 A filter magnetograph

Since the use of a filter for measurement of magnetic fields is relatively recent, it is perhaps useful to explore its potential as a magnetograph as well as its drawbacks which must be taken into account by any design meant to exploit its potential.

An obvious drawback is that optical filters do not have as narrow a bandpass as can be obtained with a spectrograph. Furthermore, the passband is not as clean nor as tuneable although the state-of-the-art in optical filters is rapidly improving in all three areas. Several advantages are obvious also. The use of filters and filtergrams have made possible real time monitoring of the sun and observation of short-lived phenomena which would not be possible with only spectrographs and spectroheliograms.

1.3 Design goals

In the design of the present magnetograph the purpose was to obtain high performance and quick and easy data reduction.

1.4 Analysis of an idealized magnetograph

As in most designs the aims conflict in that to improve one aspect, such as time resolution, results in worse results in another aspect, such as sensitivity. One must then make certain trade-offs, which for actual systems are difficult to predict in advance. One can, however, calculate such trade-offs if one leaves the real world and considers a somewhat idealized magnetograph. The idealized system we shall consider consists of a telescope with an objective lens area A and given efficiency. Spectral isolation of bandwidth λ_{BW} we will assume to be small compared to the width of the spectral line being used. The optical sensor we shall assume to be photon noise limited, so that in measuring the intensity differences between the polarized light, the uncertainty is proportional to the square root of the intensity or the number of photons detected during the time of the measurement.

The sensitivity (or uncertainty) of a magnetic measurement, ΔB, depends upon the slope and g-factor of the spectral line used. Once this is given then one can determine how the sensitivity depends upon other parameters of the telescope system and their effect upon sensitivity can be predicted from their effect on the number of photons detected per measurement.

1.5 Figure of merit

If a = the area of a resolution element

n = the number of such resolution element per raster scan

T = the time required to scan the n elements, then for a given idealized magnetograph the factor n $(\Delta B)^{-2}T^{-1}a^{-1}$ remains an invariant for a single point detector. If n, T, or a are changed in any way then ΔB increases or decreases to keep the factor constant. Because of this fact it seems to be a good candidate for a figure of merit. It is proportional to the product Ae where A is the area of the objective lens and e the overall efficiency of the system. If the magnetograph has N data channels instead of a single point detector then one has the relationship

$$\text{Figure of Merit} = \frac{n}{(\Delta B)^2 T\, a} \propto AeN \text{ (for a photon-noise limited magnetograph)}$$

Several remarks can be made about this figure of merit. First of all, it does not tell the whole story since it leaves out of consideration the ability to measure other important solar phenomena such as Doppler shifts. Versatility or ease in being able to vary n, T, and a is also not considered. Nevertheless, it does show the trade-offs in the idealized case.

1.6 Factors which determine the performance figure

That the performance figure should be proportional to the product Ae is not surprising since the photon rate per unit solar area detected by the system increases linearly with these two quantities. The presence of N in the product emphasizes the great potential of multi-channel magnetographs. For example, having two channels in place of one should give as much improvement in performance as replacing the objective lens with one with twice the area. Our approach has been to strive to increase N to the largest possible value and if necessary later increase A and e.

1.7 Scanning mode

Increasing N, however, places certain restrictions on the system. A typical Babcock magnetograph uses a single point detector (photomultiplier tube) and spectrograph with a scanning mechanism to cover the array of resolution elements under study. For purposes of illustration let us consider a 200 x 200 array. If a number of single point detectors are used simultaneously then one can no longer compensate for (and hence measure) the Doppler velocities at each point. This is the case whenever N is greater than one.

The solar magnetograph at Kitt Peak has an N = 40 by the use of 40 pairs of phototubes. This is used to scan the image in a mode which might be called a slit scan as opposed to a single point scan. Five scans of such an instrument would scan the 200 x 200 element area. A photographic method developed by Leighton and used at the Aerospace Solar Observatory also uses a slit scan producing two spectroheliograms in opposite polarity light which when subtracted yield magnetograms. This instrument can have an effective N as high as 1000.

The other scan mode is used to detect photons simultaneously in a latent image, and in this way get an effective N = 40,000 for the example above. Only a filter can be used in this scan mode, not a spectrograph.

1.8 Detector requirement

To detect a two-dimensional image with each resolution element being sampled simultaneously requires the use of film or a television-type image sensor. To use film has several drawbacks. Since the exposure time is usually short compared to the time interval between frames, this means that the time averaged efficiency is greatly reduced. Subtraction photographically is tedious and time consuming and averaging of many photographs is not practical.

Television, on the other hand, gives a signal in real time that is readily manipulated, subtracted, and averaged but the targets of television camera tubes can store the effects of only a limited number of photons before saturation. Thus if the photon rate (and thus figure of merit) is to be large, then the scanning rate must be high and that means a very high data rate. For example, standard rates are several MHz, and the amount of storage capacity required is considerable.

Two approaches are possible: analog and digital. Using analog subtraction and storage sets a limit to the signal-to-noise ratio (and thus sensitivity) attainable since any analog storage has its own noise added on. We therefore have designed for a digital system which is noise free once the data becomes digital, and there is no limit to the enhancement possible by use of signal averaging as far as the digital storage and processing is concerned. The possibility of doing digital calculations on the final data was another reason to aim for digital processing.

1.9 Storage and processing requirement

Digital data processing of digital data at video speeds places a very stringent requirement on computing equipment. It must be very fast, and have large storage capacity. To digitize the incoming data and store on digital magnetic tape is out of the question because the data rate is 4 million bits per second, and the data rates for digital magnetic tape are of the order of 40 thousand bits per second. This means that 100 tape units would have to be going simultaneously filling a 2000 ft. reel of magnetic tape each three seconds resulting in 9,600 tapes in eight hours; clearly impossible, and that would be only to store the data, not analyze it.

To compute with it in real time would be much faster than storing it, but even still only the very largest and fastest (and therefore most costly) general purpose computers would be capable of such speeds and that was out of the question because of cost. A special purpose computer seemed called for, consisting of central processor, and memory which was fast enough, large enough, and low enough in cost.

1.10 High speed, large capacity, low cost memory

The solution to the high speed, large capacity, and low cost memory appeared to be to use a digital disk or drum with a large number of heads. Disks and drums are used for slow, mass storage of data, but it seemed possible to use them in a sequential mode for data storage and retrieval at a very high rate. Although no one had used disks or drums in this way and simultaneously reading and writing is not done with the same disk or drum, there seemed to be no reason it could not be made to work so detailed plans were made using a disk in this way. The speed attained was 250 n.s. per addition or subtraction of a 16 bit value in which the data is read off one set of tracks added to and replaced onto another set of tracks. The cost of the disk we used contained about 9 million bits at a cost of about $0.004 per bit compared with the cost of magnetic core memories of about $0.10 per bit.

It turned out that using a digital disk also allowed several other features which would be impossible with magnetic core memory.

2. Principles of operation

2.1 Zeeman differences

In measurement of the longitudinal magnetic field of the sun, light from the portion of the sun under study is passed through a narrow band filter which is in one wing of the Fe I 5324Å line with a passband that is small compared to the line width. That particular line was chosen because it had a relatively large g-factor of 1.5 and was wider than the narrowest of optical filters available. Another possible choice was a very similar line at 5233Å.

The solar image is formed on the photocathode of a television tube which is scanned while the video output is digitized at approximately 40,000 points forming a 200 x 200 digital array. In this way the television image reflects the brightness digitally. When a certain point of the array comes from a region of the sun which has a longitudinal magnetic field, then Zeeman effect produces circular polarization and splits the line proportional to the magnetic field. This increases the light intensity of that point in one polarization and decreases it in the other, producing a difference ΔI at that point. The magnetic field is proportional to $\Delta I/I$ or if the response is logarithmic, ΔI.

2.2 Data reduction, two-dimensional signal averaging

It is of utmost importance that the intensity of a point in one polarization is subtracted from the intensity in the other polarization at the very same point. This requires that the telescope pointing be maintained and that the electron scanning beam within the television tube be maintained. To keep the latter in registry the rotating disk is used as the master clock of the system sending out three types of pulses all proportional to its rotation speed. Each clock pulse of the disk (approximately 3, 9 MHz) causes a pulse to go to the analog-to-digital converter; each 256 clock pulses sends a horizontal line pulse indicating a new sweep of the scanning beam and each 256 horizontal line pulses sends a vertical line pulse to start a new vertical scan. The clock pulse has precisely 256 x 512 pulses so that each rotation is two fields.

Frames representing different circular polarizations are added or subtracted. The result is that the signals due to magnetic fields add while the noise being random sometimes adds and sometimes cancels. The end result is that the signal goes as N where N is the number of frames while the noise (or uncertainty) goes as $\sqrt{N}$, thus giving a signal-to-noise enhancement proportional to $\sqrt{N}$. To our knowledge this is the first application of digital signal averaging of signals for two-dimension difference images.

2.3 Data presentation and further analysis

At this point the magnetic field data is digital and difficult to interpret. For display of the results each of the 40,000 values is converted into a 3 bit number representing eight brightnesses and stored on three tracks of the disk devoted to display. These three tracks are fed to a digital-to-analog converter which is fed to the video input of a television monitor which then displays the resultant magnetic fields. A movie camera is ready to record this display and may be triggered by the computer under program control.

The original, 16 bit data can be stored on digital magnetic tape for further data analysis, or short analyses can be done by the general purpose computer while the next magnetic field is being calculated. A limited number of calculations can also be done by the high-speed special purpose computer such as measuring distributions or percentiles over particular regions of interest using a light pen if necessary.

3. Description of equipment

3.1 Optical

The optical system consists of a 6" diameter, 48" objective lens, 45 degree mirror flat, aperture stop of polished metal at the prime focus, enlarging lens which can have a focal length of 50 to 100 mm, another 45° flat, quarter wave plate which can be flipped or KDP crystal, narrow band filter and SEC camera tube.

In a typical arrangement the overall F/no of the system is 50 with a field of view of 400 arc second, though it can be smaller or larger.

3.2 Polarizer

At the time of the writing the KDP crystal has shattered and the polarizing changes are produced by a mica quarter wave plate which is flipped by a stepping motor.

3.3 Optical filter

The optical filter is a hybrid filter with a solid Fabry-Perot mica spaced filter followed by four birefringent elements of calcite. This is patterned after the filter developed by Harry Ramsey.

3.4 Video camera and signal

The television camera is a Westinghouse SEC tube which has target magnification, good sensitivity, high target capacity, and low lag.

It has an automatic gain control feature which automatically adjusts the target high voltage which changes the multiplication which occurs at the target to correct for the light level.

The video signal is then amplified by a low noise preamplifier followed by an additional amplifier with adjustable gain which we built to adjust the output to the analog-to-digital converter. The digital-to-analog converter converts the signal to an 8 bit value on command each 250 n.s. and inputs the result into the high speed adder or subtractor.

3.5 High speed special purpose computer

This adder-subtractor circuit adds data from 16 tracks to 8 bit data from the analog-to-digital converter or from a special register. By use of this register a given constant can be added or subtracted from all of the data. A counter counts the number smaller or larger than the number in a frame or a selected portion of a frame which has been stored on a special "mask" track. By the use of this bias register, accumulation counter, and mask track, brightness distributions can be very quickly created, and arrays of 16 bit numbers can be quickly reduced to arrays of 3 bit numbers. The mask tracks can be generated by the general purpose computer, the light pen, or the picture itself if region of interest is bounded by a contour.

The data in this high-speed section of the disk processes four bits each addition cycle because of delays so a special origin counter keeps track of the data in this part of the disk.

3.6 Display section

After the data has been converted into 3 bits, it is transferred to three special tracks connected to an analog-tc-digital converter which feeds into a television monitor. Actually there are two such 3 bit ADC's and two 1 bit ADC's with provision for more if required (for example for color). On the single display tracks alphanumeric data can be placed or graphical data can be displayed.

3.7 Storage and analysis sections

Thirty-two tracks of the digital disk are available for storage of data. Data can be transferred between different parts of the disk either track by track or eight tracks at a time, and between the disk and the general purpose computer by use of a buffer which is 2048 bits in size and can operate either at high speed for transfers to and from the disk or at low speed for transfer to and from the general purpose computer.

The general purpose computer is a Varian Data Machine 620i computer equipped with digital magnetic tape units for storage of magnetic field data as well as for input of computer programs for different programs.

4. Performance analysis and problems

4.1 Sensitivity

We shall divide the discussion of performance into those factors which affect the performance figure of merit mentioned in the introduction (which reduces to sensitivity when resolution, time, and size of the array are held constant) and other criteria such as resolution and versatility.

Because all data manipulation downstream of the ADC is digital, the factors affecting the sensitivity (or figure of merit) is limited to three: guiding and seeing variations, spectral and polarization purity, and video signal-to-noise.

It is expected that over the next two years further improvement in these three areas will improve the sensitivity by a factor of about thirty so that very weak fields can be studied. At present the limit for reasonable times and moderate resolution is about 40-50 Gauss, the levels found at supergranule boundaries.

4.2 Resolution and versatility

For changes in fields in short times at least better guiding is necessary. Due to delays particularly caused by the February 9, 1971 earthquake our guider is not yet operational, giving us lower resolution and false fields at the edge of sunspots.

By versatility we mean ease at programming and adapting to study certain solar problems of interest. These include measurement of magnetic gradients and changes and nonmagnetic studies such as Doppler velocities, fast Hα brightenings, production of 10830Å He spectroheliograms. For these latter other television cameras will feed data to the digital video processor; these cameras can be fed by filters on the spectroheliograph. Adaptation of the Aerospace spectroheliograph was underway for use with a silicon diode array for 10830Å spectroheliograms when the earthquake struck. Ed Frazier of Aerospace has designed Hα and Ca K optical telescopes with filters and television cameras for video display as well as time lapse photography on film. After completion of these systems it should be relatively easy to feed these images and analyze them as well. It should be a relatively easy task to adapt the system so that it can perform such tasks in a time sharing mode with magnetic field measurement.

5. Results

5.1 Comparisons and calibrations

The videomagnetograph was put into operation (though not yet complete) on October 19, 1970 (aside from some preliminary low sensitivity results in July 1970) and operated, weather permitting, for a little over three months until February 9, 1971 when the Sylmar earthquake struck and did considerable damage. During the three months of operation the winds prevented operation of the Aerospace 24" photographic magnetograph during most of that period, but on

January 14, 1971 magnetographs were taken simultaneously by both magnetographs. After the earthquake the videomagnetograph was put into operation again on April 22 at which time a magnetogram of the same region was made at the Kitt Peak magnetograph. These comparisons are shown, but because the sensitivity has since been improved the comparisons do not serve as a calibration.

5.2 Analysis of videomagnetograms

Magnetic movies covering a two-day period were made on May 18 and May 19 on McMath plage 313. This interesting region produced two subflares during this period and a class 2 flare some eight hours later. It is a bipolar magnetic region with only one large spot but with a long tight gradient along the neutral line. Time lapse videomagnetograms were made each 15 seconds and digital videomagnetograms were stored digitally each 5 minutes. The time lapse movies do not show obvious magnetic changes. Preliminary digital studies show changes, but at this time how much can be attributed to guiding errors and seeing is not yet known. This analysis is continuing and will be presented at the AAS meeting at Amherst in August 1971.

APPENDIX A - NARROW BAND OPTICAL FILTERS

A.1 Filter Characteristics

The development of new and better optical filters is progressing rapidly at this time, a fact which is very promising for solar research. We would like to mention here some of the most important characteristics to consider when evaluating filters, then mention the various types of narrow band (one Å or less) filters, and finally mention what three types have a special appeal at this time.

The filter characteristics which seem most important to be kept in mind are:

- spectral bandwidth
- spectral purity
- angular sensitivity and possible field of view
- resolution
- image quality through the filter
- uniformity across the image in transmission and wavelength
- tuneability
- ease of use, weight
- polarity of transmission
- aperture size
- length
- cost

A.2 Types of filters

Heat rejection filters - These filters are important in solar telescope to keep out heat which could cause heating and internal seeing effects or could cause heating and degredation of a prefilter. Ideally they should be several Angstroms wide and well blocked in the infrared and ultraviolet.

Prefilters - These typically are 3Å to 20Å bandpass and are meant to block out side bands of the narrow filter. Often not enough attention is given to the prefilters and not uncommonly telescope systems are down because of failures in prefilters which often drift. A report by Alan Title is very useful here.

Birefringent filters

Lyot-Evans "folded filter" - These are the work horse of $H\alpha$ patrol filters. They are often tuneable, with a large acceptance angle, yielding pictures of good image quality. They transmit only one polarization generally, typically have small transmission, and are limited to how narrow they can be made.

Solc "fan filter" - As yet this filter has not seen wide use in solar astronomy. Evaluation will have to follow use and testing.

Multi peak filter - A filter which can operate in several lines simultaneously should be mentioned as a possible variation for completeness sake. One such has been built and used at Sacramento Peak Observatory though this author is not familiar with its present state of development or use.

Fabry-Perot filters - We will briefly treat three types of Fabry-Perot filters: air spaced, mica spaced, and glass spaced. One general advantage of the Fabry-Perot is that it does not necessarily polarize the light and hence it is theoretically possible to have two filtered images formed simultaneously in different polarizations with the same seeing variations in each image. In the deficit column they tend to be very angular, sensitive, requiring small aperture lenses or small fields of view or both, and since light passes many times between the mirrors, the constraint on the optical quality is stringent.

Air spaced - The Giovanelli-Ramsay filter developed by CSIRO in Australia has achieved very narrow bandpasses (up to 0.05Å) and good resolution. The triple filter is very large and probably should be used in a laboratory environment (e.g. fed by a horizontal heliostat) rather than mounted on a spar. The author would like to have more information on ease of operation before more detailed analysis. Another air spaced filter which should be included for completeness is the PEPSIOS filter which in principle can be used for images, though in practice it may never have been so used.

Mica spaced Fabry-Perot filters - These generally are in the range of 0.5 to 2Å bandpass, and require high quality mica for their fabrication.

Glass spaced Fabry-Perot filters - Prototypes have been constructed by Russ Austin at Perkin Elmer. In principle they can be made very narrow. They are thin and lightweight and high transmission.

Resonance absorption filters - These can be used only for very few lines where a suitable absorbing vapor exists.

Gyromagnetic polarizing interferometer GYMPI filter - This new type is mentioned in JOC 48 (1958) and Applied Optics, May 1971 but is still developmental with some practical problems which seem similar to those experienced at NASA MSC Houston while attempting to develop a spherical Fabry-Perot filter. The GYMPI uses rotation by the Farraday effect by magnetic field in between Fabry-Perot plates (or spheres).

Microwave filter - Rotation by microwave is being used in a filter under development by Harris at Stanford.

Passive Birefringent Fabry-Perot filter - It is pointed out in JOC 61, 6 (1971) that what is attempted in the above two using Farraday rotation should be attainable using a passive birefringent crystal and two quarter wave plates between Fabry-Perot mirrors. To our knowledge this has not yet been reduced to practice.

Hybrid filters - The filter developed by Harry Ramsey at Lockheed uses a mica spaced F-P filter as prefilter to three or four birefringent elements. The beauty of this is that side bands are reduced further than is possible with either type above and the angular acceptance is very high. One could possibly not go down to 0.05 Å bandpass with these.

A.3 Filters of special interest

Filter technology is advancing rapidly at this time and may make new types of solar observation possible. Of particular interest is the actual performance possible with the glass spaced F-P filter and the passive birefringent F-P filter.

APPENDIX B - TELEVISION TYPE IMAGE SENSORS

B.1 Types of video sensors

Television type image sensors include the following types:

- vidicon
- image orthicon
- plumbicon (Phillips Lab)
- silicon diode array (RCA, Texas Instruments, Amperex, Hughes)
- secondary electron conduction, SEC, (Westinghouse)
- silicon electron bombardment induced conductivity

  (Phillips calls their tube the EBIC for electron bombardment induced conductivity)
  (RCA call theirs SIT for silicon impact tube)
  (Westinghouse calls theirs EBS for electron bombardment silicon)

- image isocon (RCA)
- return beam vidicon
- solid state mosaic sensors

B.2 Signal-to-noise analysis of plumbicon and silicon diode array

From the viewpoint of measuring magnetic fields or on any other subtractive measurement such as Doppler shifts or temporal changes, the most important characteristic of the TV tube is its signal-to-noise ratio. It is instructive to look at those tubes listed above which have the highest S/N ratios and see what factors determine this value and what are the limits that are possible to attain. Let us first consider the plumbicon tube with a PbO target and a silicon diode array tube. These tubes are similar in that they have photoconductive targets with high quantum efficiency of order 0.5 whose target is read with a scanning electron beam. The video signal is amplified by a low noise preamplifier.

There are two major sources of noise: shot noise and preamplifier noise. At high light levels it is the preamp noise which is dominant. The state-of-the-art in low noise preamps is about 2 nA noise at 5 MHz. The maximum signal is given by the storage capacity of the target which is typically 500 nA for the plumbicon and 800 nA for the silicon tube. This would set a limiting S/N ratio of several hundred in principle. This sounds extremely good, but falls rapidly with intensity. At a light level ten times lower the S/N would be down to several tens, and if the light level were raised then saturation would occur. This means that these tubes have a very narrow range of high signal-to-noise ratio. In the region where the S/N due to the preamp is high, the shot noise is very low in comparison.

B.3 Signal-to-noise ratio for the SEC and Silicon bombardment tube

The SEC and SIT (to use RCA's name) tubes differ from the plumbicon and silicon diode array in that they have a photoemissive photocathode (usually S-20 response) whose electrons when released are accelerated through a high voltage and focused on a target where one high energy electron produces many electron-hole pairs. The target of the SEC tube allows an almost noise free electron multiplication at the target of 50 to 100 dependent upon the value of the high voltage in the accelerating section. The SIT target electron multiplication goes from about 20 to 2000 as the high voltage goes from 4KV to 12KV. In the previous case of the plumbicon and silicon tubes over the entire range where the signal-to-noise ratio was large (over 10 say) the S/N ratio was determined by the noise in the preamplifier. The almost noise free target amplification of the SEC and SIT tubes greatly extends the range of light levels where the S/N ratio is large.

With the SEC and SIT tubes the target capacities are different. The SEC has a maximum signal current of about 100 nA while the SIT maximum signal current is about 600 nA. For a preamp with 2 nA noise current at 5 MHz this means the maximum S/N ratio because of preamp noise would be of 50 and 300 respectively. The other source of noise which must be added in quadrature is shot noise at the photocathode. At 5 MHz this shot noise is approximately $S/N = 30\sqrt{S}$ where the photocathode signal current S is expressed in nA. The result is that these tubes are much more sensitive and have large signal-to-noise ratios over large ranges of light level. The new SIT tube is superior to the SEC both at lower and higher light levels because of its greater target multiplication and its greater target capacity.

APPENDIX C - DATA HANDLING TECHNIQUES

One of the authors of this report (N. K. Baker) has contributed to a larger Aerospace report dealing in depth with questions of data handling of images entitled "Supplementary Information for a Technical Proposal: Density Manipulation Subsystem." A copy of this report is being sent to Donald Robbins, MSC, Houston.

APPENDIX D - VIDEOMAGNETOGRAPH IMPROVEMENTS

D.1 Possible improvements due to better optical filters

The sensitivity of a magnetograph goes approximately as the product of $g\lambda^2$ and the slope of the wing of the line being used. The line being used Fe I 5324 has certain advantages, namely resistance to magnetic saturation and resistance to changes due to Doppler shifts (including solar rotation), but for greatest sensitivity a narrower line with larger g factor would be better but a narrower line cannot be used until a filter is available which is narrower still. Existing and prospective narrow band filters are summarized in Appendix A, and when a suitable filter becomes available an increase in sensitivity due to the spectral line could be as much as a factor of 10.

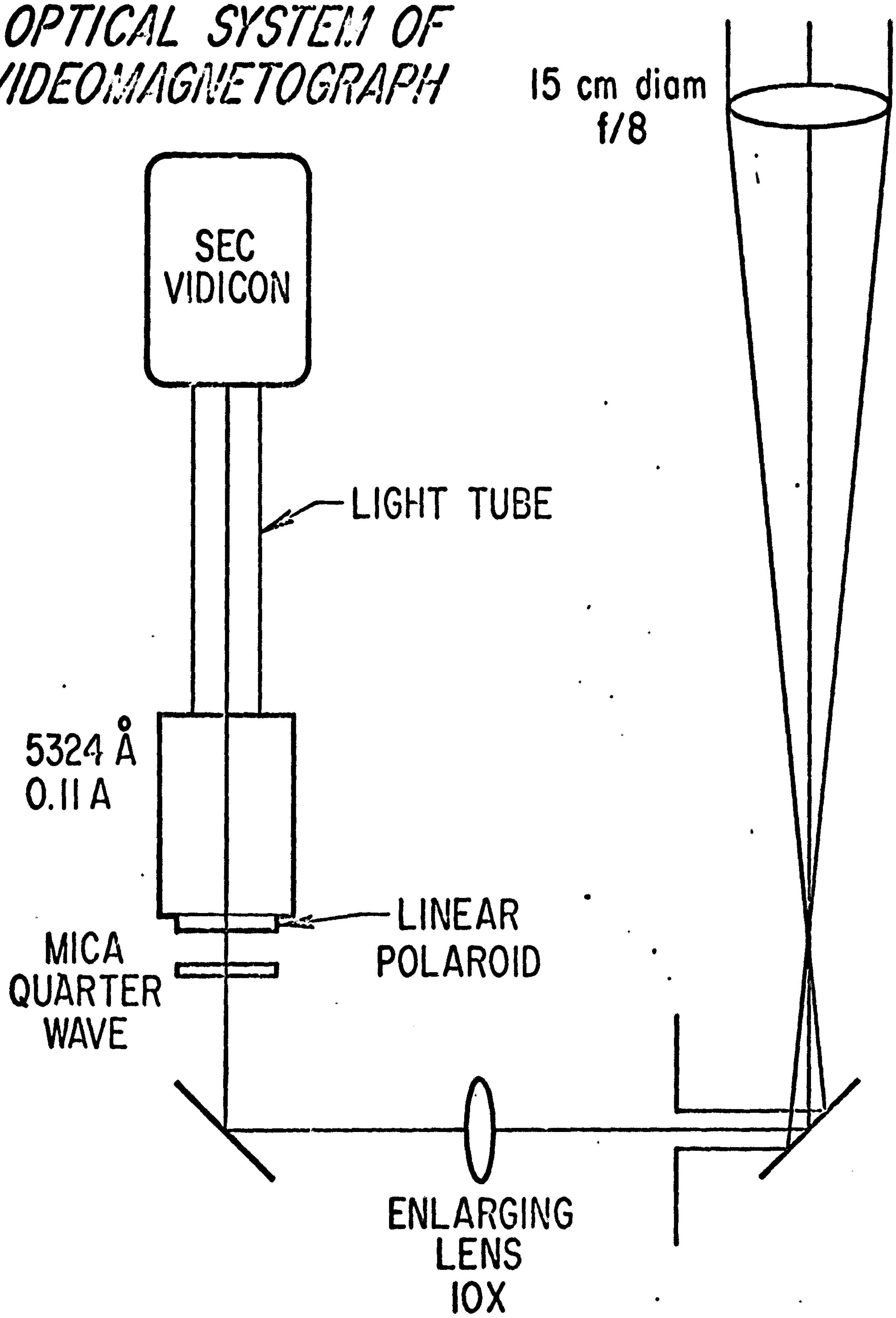
D.2 Possible improvements due to guiding and seeing

Temporal changes in the image during the measurement of a magnetograph are very important, and affect the sensitivity and resolution. Four improvements could make a great deal of difference. First is a better guider for our spar (we are now trying out our prototype guider while operating on clock drive). Second is a fast acting guider which moves the image only by tilting one of the folding mirrors. Motion of the mirror (or a tilt plate) could be done with piezo-electric crystals holding the mirror cell or hot wires working against springs as has been done by Stenflo. The sensor for the motion of the image plane might best be an image dissector tube continually monitoring the position of a sunspot or other solar feature. Thirdly would be the use of KDP crystal for rapid switching of polarization. At present our KDP is shattered and the replacement has not arrived. In the meanwhile we are flipping a quarter wave plate mechanically about once per 2 or 3 seconds. Fourth would be a larger aperture objective for periods of best seeing with and optical system without the folding mirrors which collect dust and are a source of unwanted light. Two of these improvements are underway and two are further downstream. In general these improvements take more time than money and are ideal tasks to undertake during the winter months. Fortunately these improvements would not cause substantial interference with an observing program. The improvements gained would probably be a factor of 10 or more.

D.3 Possible improvements due to television S/N ratio

Television camera tubes and their signal-to-noise ratio are summarized in Appendix B. Improvement here of a factor of 3 should be possible with our present SEC camera tube and by use of the SIT tube a much greater improvement is expected. Since filter technology and video technology are both advancing rapidly at this time, it is encouraging that the digital video processor can relatively easily take full advantage of these improvements.

OPTICAL SYSTEM OF VIDEOMAGNETOGRAPH



REAL TIME COMPUTER PROCESSING OF VIDEO IMAGES

T. J. Janssens and N. K. Baker
San Fernando Observatory
The Aerospace Corporation
El Segundo, California

E. E. Robbins
NASA Manned Space Center
Houston, Texas

Introduction

Origin of the technique - The technique of digitizing and computing with television images in real time grew out of a specific task; namely, the measurement of solar magnetic fields, and perhaps it is best to illustrate the technique by describing this particular measurement.

To measure solar magnetic fields by use of Zeeman splitting and polarization of a Fraunhoffer line requires the spectral isolation of light from just one wing of a magnetically sensitive line, detection and subtraction of the light intensities in right and left handed circular polarizations, and a scanning process which repeats this process for each point on the sun under investigation.

Figure of Merit for an Idealized Magnetograph - A high performance solar magnetograph would look at a large section of the sun with high spatial resolution, high sensitivity, and high temporal resolution.

If we let ΔB = the magnetic uncertainty
a = the area of resolution cell
T = the time for a scan
n = the number of resolution elements per scan,
then for an idealized point scanning photon-limited solar magnetograph, the ratio $n/(\Delta B)^2 T a$ remains invariant with the magnetic uncertainty, ΔB, changing as the other three parameters are adjusted. The ratio depends only on the rate of photon detection per cell area and is proportional to the product $A \epsilon N$ where A is the area of the obective lens, ϵ is the overall efficiency and N is the number of data channels. Using the ratio as a figure of merit we have:

$$\text{Figure of merit} = \frac{n}{(\Delta B)^2 T a} \quad \alpha \quad A \epsilon N$$

which shows that for this idealized consideration the figure of merit is increased by enlarging the lens, raising the efficiency, or increasing the number of channels. This approach is an attempt to increase the effective number of channels.

The Scanning Mode - Consider three modes of scanning and their effective number of data channels for similar resolution and area of interest of 40,000 points. The most usual method is a point-by-point scan with an effective N = 1.

A method developed by R. B. Leighton involves simultaneous spectroheliogram pairs whose difference yields a picture of the magnetic fields. This slit scanning for this example has an effective N = 200 although in practice it may have N of about 1000.

The third method of scanning detects photons from all parts of the image simultaneously. This has an effective N = 40,000 but requires spectral isolation by use of a very narrow integrating detector such as film or a television type camera.

Detector and Data Processing Requirements - Use of film is impractical if one wishes to maximize the rate of photon detection because of the large quantities of film required and the difficulties with photographic subtraction, but with television other problems are encountered.

To maximize the photon detection rate, the television tube is scanned at a fast rate (standard TV rate) since the target of a camera tube can hold only a given number of photoelectrons before being read off.

The usual method of data processing is to digitize and store on magnetic tape for later analysis but here a problem arises. The video data rate is 4 million bytes per second compared with about 30,000 bytes per second for a typical magnetic tape recorder. Thus for a straightforward approach 133 tapes recorders would be required and since a reel of tape holds about 10^7 bytes, reels would be filled at the rate of one each $2\frac{1}{2}$ seconds or 14,400 tape reels in 10 hours.

Real Time Computation- This severe case of data poisoning could be solved by computing in real time since a great many frames are added and subtracted to give a resultant magnetic picture, but for a general purpose computer the memory size and speed would be prohibitive.

To solve the problem a very high speed arithmetic unit was combined with a digital magnetic disk used with parallel, sequential access instead of random access. The disk has 72 tracks and 131,000 bits per track, and rotates at 30 Hz.

Discription of the System

Organization - For convenience, the digital system shown in Fig. 1 is divided into three working areas:

1. A data gathering section where the raw data are collected as a 16-bit digitized array.
2. A display section where the data are reduced to 4 bits (8-16 gray levels).
3. A data storage section where two 16 bit frames, or four 8 bit frames, or 16 bit-bit frames can be stored temporarily.

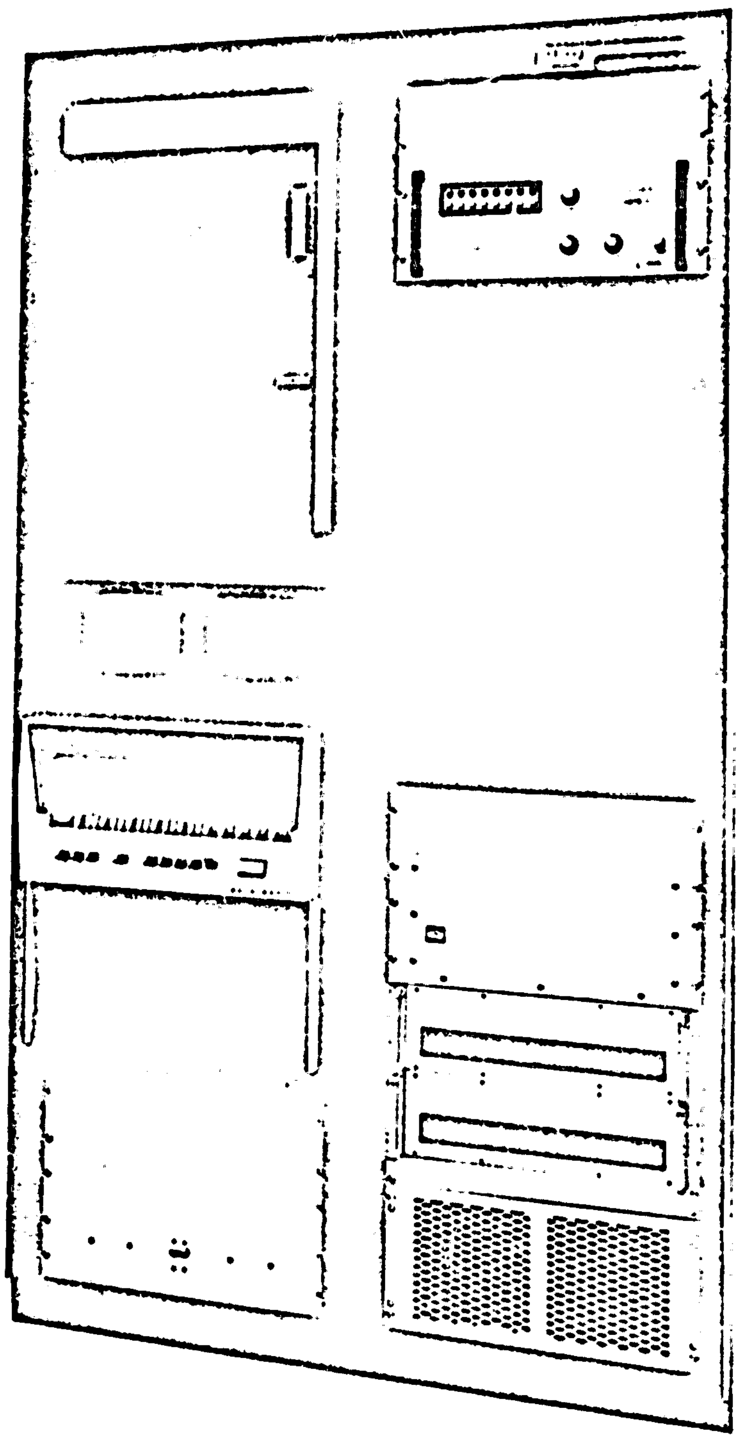


Figure 1.-Digital video processor. On the left is the ADC, high speed adder, and digital magnetic disk. On the right is the magnetic tape recorder, output displays, and general purpose computer. Now shown in the light pen.

Data Gathering - The data gathering area was designed to accept an analogue signal from a TV camera which was synchronized with the disk's rotation speed. This signal is digitized into 8 bits (256 levels) by a 4 megacycle convertor which is synchronized with the data flow of the disk. The output of the analogue to digital converter can be added to or subtracted from a previously stored array in the data gathering area of the disk and then stored, thereby erasing the previous image array. This operation is controlled by the disk interface controller which requires one instruction per frame whether to add or subtract the incoming image. It is operated on an interrupt basis by a small general purpose computer attached to the system.

After the completion of the data gathering mode, the system can be interrogated for information on the entire frame. At present, we can get the number of elements greater than a certain value, value of the nth largest element and mth smallest element, or the average value. The position of the element cannot be found in this interrogation mode.

For instance, the time to obtain the nth largest element in the array of 100,000 points is 0.5 second. This information is mainly used to set the levels for the display and to make distribution plots.

Display and Light Pen - In the display section, we have a variety of choices, ranging from arbitrary selection of 8 to 16 gray levels to automatic selection by the computer. The display can be in either a positive or negative mode, logarithmic or linear scaling. These display data are transferred to the display section of the disk and displayed to the operator. The 4 bit (16 gray levels) data is connected to a digital to analogue convertor and fed to two TV monitors which are synchronized to the disk. The operator can use a light pen on the monitor to select points or areas on which he wants more information, such as the numerical value of a specific point or position of the point. For areas, the operator can define rectangles or circles of various sizes in which he wants average values, maximum value, or minimum value.

The display section can also be used for graphic and alphanumeric display of the data, ranging from intensity plots on arbitrary cross sections of the picture to distribution plots of the entire frame.

Storage - The data storage area is used as an intermediate storage to free the data gathering area. From this area, the data can be transferred to permanent storage on tape. It can also be used to hold image correction data which the computer could use to correct the raw data for imperfections or shading in the TV camera.

Present Status - At the present writing the system is completed but with two remaining problems which are now being solved. One is recurrent failures of one of the digital components which has now been replaced and the other is switching the polarization of the image without hurting the image quality or registration. (NOTE - Successful operation began on July 17, 1970.)

Tests on multi-image enhancement (essentially 2 dimensional signal averaging) have shown that the noise is indeed Gaussian in nature and hence sensitivity does increase as $\sqrt{n}$ where n is the number of frames involved.

Possible Other Applications

General Considerations - Applications of real time computing on video images might include studies of 2 dimensional scenes especially where the measurement is of differences with certain variables such as wavelength (Doppler, color indices), polarization (synchroton, Zeeman), time (pulsations, sudden eruptions). Other applications capitalize on one or more of the special features, e.g., the ultrahigh speed processing, the two dimensional signal averaging, the real time computations by the general purpose computer, the immediate display with man-interface interaction, and the data compression.

We may symbolically characterize a scene to be studied as

$$Z = I(x,y,\lambda,p,t) + j(x,y, \quad ,p,t)$$

where I = intensity of the object
x,y = spatial variables
λ = wavelength
p = polarization
t = time
j = perturbations from the detector, atmosphere, etc.

The two dimensions on the tube face are usually x and y but could be λ or some other variable. Most measurements would involve enhancement of differences due to variations in one or more variables while the effects of perturbations are minimized.

An Example - A simple illustration might be the search for an optical pulsar when its frequency is known but not its exact position. If a telescope equipped with image intensifier and television camera tube had its video taped output played back into this system and alternately add and subtract frames separated by half the pulsar's period, then when the phase was right only light coming from the pulsar should fail to cancel.

Another example might be two dimensional photon counting though this would require additional preprocessing. The dimensions could be spatial or spectral.

TIME-LAPSE VIDEO MAGNETOGRAMS

N. Baker and T. Janssens

Space Physics Laboratory
The Aerospace Corporation
El Segundo, California 09245

*Text of a Presentation at the First Meeting
of the Solar Physics Division of the
American Astronomical Society, Huntsville, Alabama
November 17-19, 1970

TIME-LAPSE VIDEO MAGNETOGRAMS

by

N. Baker and T. Janssens

The Aerospace Corporation
Space Physics Laboratory
El Segundo, California

ABSTRACT

Real time solar magnetographs were obtained over a one month period using the Aerospace-NASA videomagnetograph which employs a hybrid 0.1 A filter at 5324 A and a SEC television tube. The image was digitized into an array of 40,000 elements and time averaged at 30 frames per second. Time sequences of video magne- ms encompassing a region of 300 x 300 arc secs were recorded on digital tape at intervals of two minutes. The sensitivity obtainable with this time resolution was about 40 gauss/element where the element size was 2 arc seconds. A film was made from selected portions of the data tapes. Distributions of field strengths of selected regions were also obtained.

High resolution solar magnetograms from the Aerospace 24" telescope and spectroheliograph were made simultaneously for comparison.

I. Introduction

During the past few years, we have constructed a real time magnetograph employing a video system and a digital picture processor. This combination produced a system which not only obtains magnetic fields, but also aids the observer in analyzing magnetic field regions.

Magnetic fields have been obtained through either filter or spectrographic techniques. The filter has the advantage that the entire image is taken at one time, but has the disadvantage of limited spectral range and reduced spectral purity. As a sensor for the filter system, film or vidicons could be used. Real time results could not be achieved by using film as the sensor and photographic subtraction techniques to obtain the field regions. In addition, the film has to be eventually digitized to obtain quantitative data out of it. The vidicon, on the other hand, does not have the resolution of film in either spatial or gray level coordinates. It does not have film's signal-to-noise ratio, but the original signal is available for digitizing. For many purposes,

Real time data acquisition was important ~~to us~~. Therefore, we designed a system using a SEC vidicon. To improve the signal-to-noise ratio of the system, we decided to use signal averaging on each point in the frame over a number of television frames. But in order to maximize the photodetection capabilities of the television tube, the tube had to be scanned at normal TV rates. We were led to design a picture processing unit which would be capable of digitizing any television signal into 256 levels at a rate of four million words per second.

The unit had to perform certain specified operations such as addition or subtraction of entire TV frames in order to do our signal averaging. Thus, using this combination system of a picture processing unit, a SEC vidicon tube, and a hybrid filter, we were able to obtain magnetic field pictures in less than one minute and display them in various modes to an operator.

II. The Optical System

The optical system of the videomagnetograph is illustrated in the first figure. The f/50 telescope is mounted on a spar which will eventually contain two other vidicon telescopes directly connected with the picture processing unit. The computer can select the polarity of the light entering the filter by setting a quarter wave plate and polaroid to the proper orientation. The necessary spectral isolation is achieved by a hybrid filter with a bandpass of 0.11 A, similar to the filter developed by H. Ramsey of Lockheed. The filter is tuned by a temperature control to the blue wing of the 5324 A line of Fe I. This line was chosen for its equivalent width and the moderate g factor.

A real image, 300 arc secs on a side, is formed on the face of the SEC vidicon. The vidicon has an effective array of 232 x 232 picture elements which is scanned at 60 hertz. The spatial resolution is therefore about 1.5 arc seconds/element.

III. Picture Processing Unit

The picture processing unit does signal averaging, differencing, data analysis, display, and storage of data. It consists of a general purpose computer (a Varian 620/i) and a large digital disk capable of storing two 16 bit pictures and five 8 bit pictures at one time. An 8 bit analogue to digital convertor digitizes the incoming video signal at four megacycles. The data is then signal averaged with the picture data on the disk. Every sixtieth of a second, 50,000 elements are averaged and stored for the next cycle. In 256 100 additions, we can improve the signal to noise (due to random fluctuations) by a factor of 16. 32

To produce a magnetic field picture, it is desirable that two simultaneous pictures taking in right and left circular light be subtracted. We cannot make true simultaneous pictures of both channels, but we do alternate between polarities every second as we build up a signal averaged picture. The magnetogram in figure 3 had an integration of 1,000 pairs or approximately one minute of integration time. The maximum integration time is limited by numerical overflow at about ten minutes.

After the signal averaging stage is complete, the system displays to the operator a 16 gray level representation of the magnetic field as is shown in figure 3. Normally, we set the zero field value at an average gray level and use black for the strongest negative fields and white for the strongest positive fields. The individual gray levels can be set to any arbitrary values or to any calculated values, such as to definite percentiles of the picture, logarithmic scales, or linear scales. In the figure, a linear discrimination was used between a maximum and minimum value set by the operator. The magnetic field pictures could also be displayed in the form of contours.

By ~~But~~ having a general purpose computer on line, we can also do some real time numerical analysis of the image. Numerical distributions for the entire frame or selected regions are displayed to the operator on the display console in the form of graphs. The computer can display graphs of the intensity along any straight line. Other possible routines include cross-correlation, calculation of centroids of positive and negative field regions, maximum and minimum values in specified areas of the frame, or a standard deviation from zero field. Many calculations can be done while a new magnetogram is being acquired because of the large storage capacity of the disk and the interrupt system used in the control of the unit.

We have aimed to build in the system features which are not available on the film. We can display absolute fields and change the contrast levels to bring out variations in the fields. We can enlarge a picture to any scale about a region selected by the operator for further analysis. The enlargement capability helps the operator obtain specific gray level information in a complex area. A gray code is displayed to help the operator identify levels. In the future, we are planning a color display system where each color would represent a certain gray level. We can also display either a negative or positive picture.

• many pictures 3-10'

We do have a problem storing the 10^6 bits per picture. At present the computer controls a 16 mm camera which has its own display. A polaroid camera is also used to obtain pictures for immediate posting. If the digitized array is to be saved for a length of time, it is stored on either 9 or 7 track digital tape. These tapes can be analyzed by the system at a later time or taken to a larger computer.

The picture processor is not limited to obtaining magnetic fields. Radio maps (3 mm), satellite photographs, and solar UV data have been displayed on the system. Any digitized .ture array is a candidate for display.

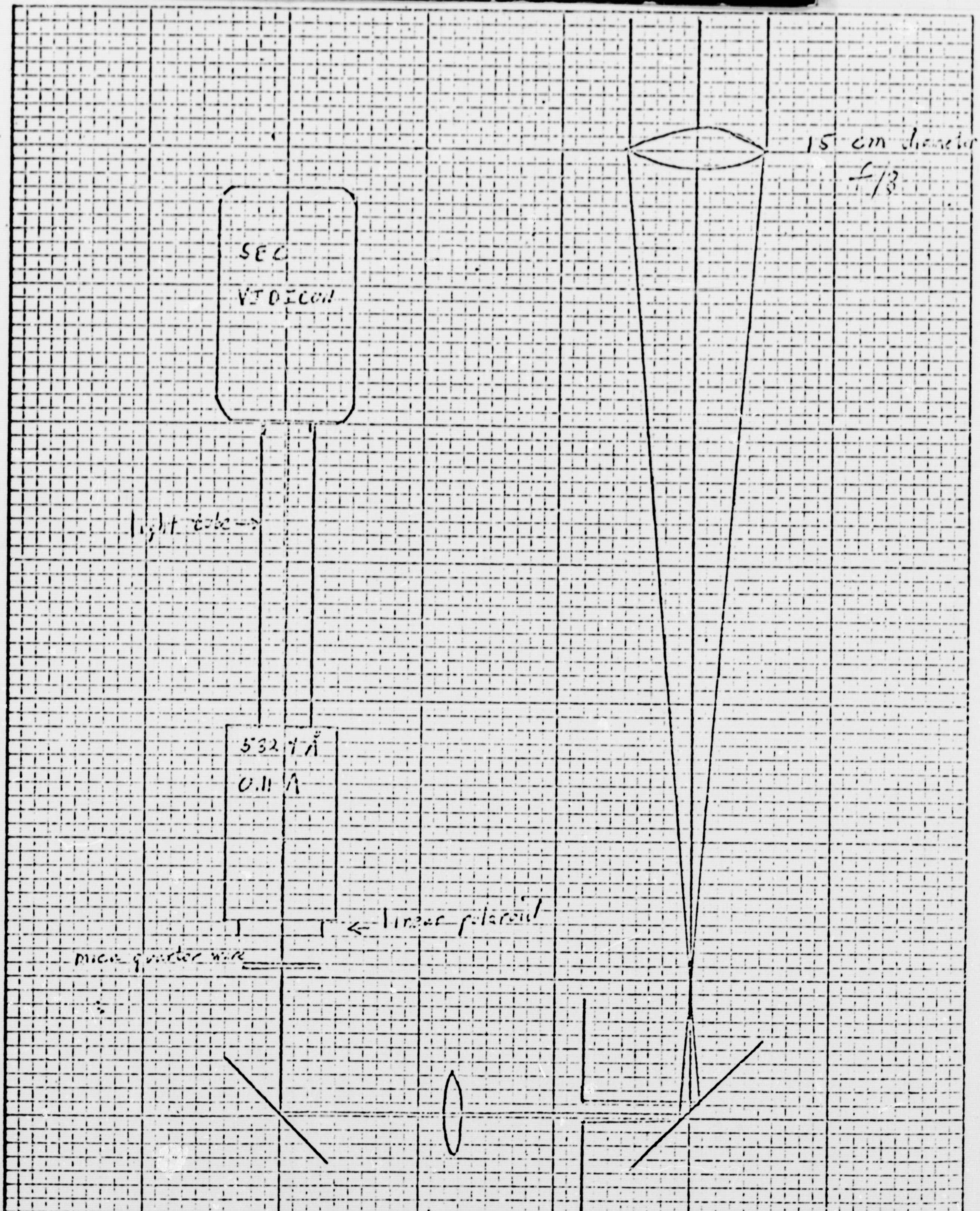
IV. Examples

Figure 3 is an example of the type of magnetic field information that we have obtained. It is unfortunate that we have not been able to calibrate the system as we are still trying to improve its performance. The seeing was only fair when this photograph was taken. The field strengths shown probably range from 100 gauss to 3,000 gauss. Note the numbers on the frame do not correspond to gauss, but are the range of the actual digitized numbers.

Figure 4 is the same region as figure 3 taken a few days earlier. Unfortunately this was taken as a negative display. The integration period was longer for this frame. We can trade off time for sensitivity. If we integrated four times longer, we should increase our sensitivity by a factor of 2. But in actual practice this does not happen because the seeing averages some of the data out.

As our last example, we have a time lapse movie which was reregistered from the original. The computer was given a simple program to just obtain a field picture, display, and activate the film camera. The seeing changes required a reregistration of the film.

We would like to express our appreciation to NASA for their support, especially to Don Robbins of the MSFC for his continual collaboration. E. B. Mayfield, G. A. Paulikas, and R. A. Becker of The Aerospace Corporation have given us a great deal of support. We would not have been successful without the technical help of Greg Kozlowski of Aerospace and Dave Rutland of Spatial Data Corporation.



OPTICAL SYSTEM OF VIDEOMAGNETOGRAPH

figure 1

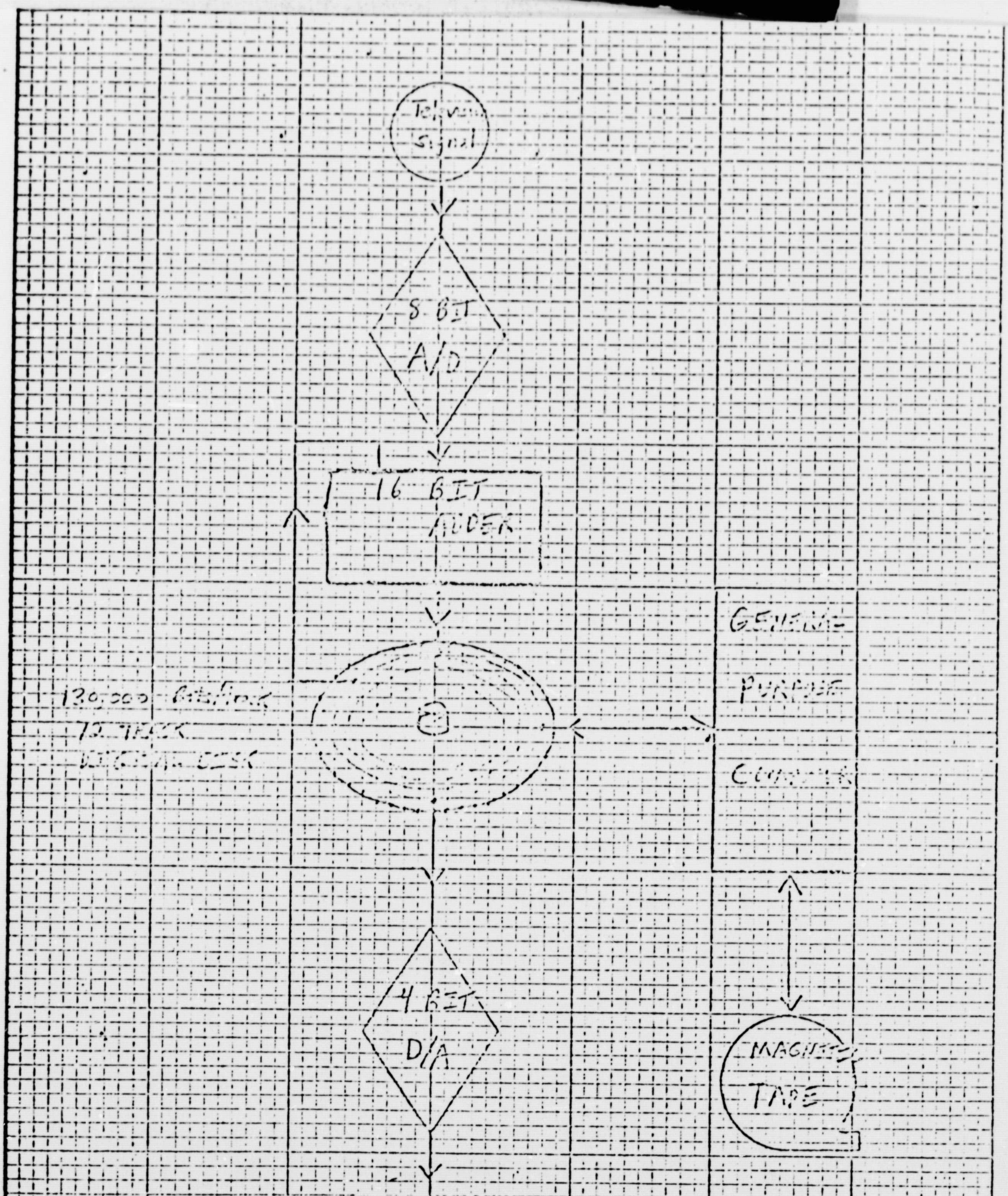

8 BIT
A/D
16 BIT
ADDER
PURPOSE
4 BIT
D/A
TAPE
VIDEO - DIGITAL PROCESSOR

FIGURE 2

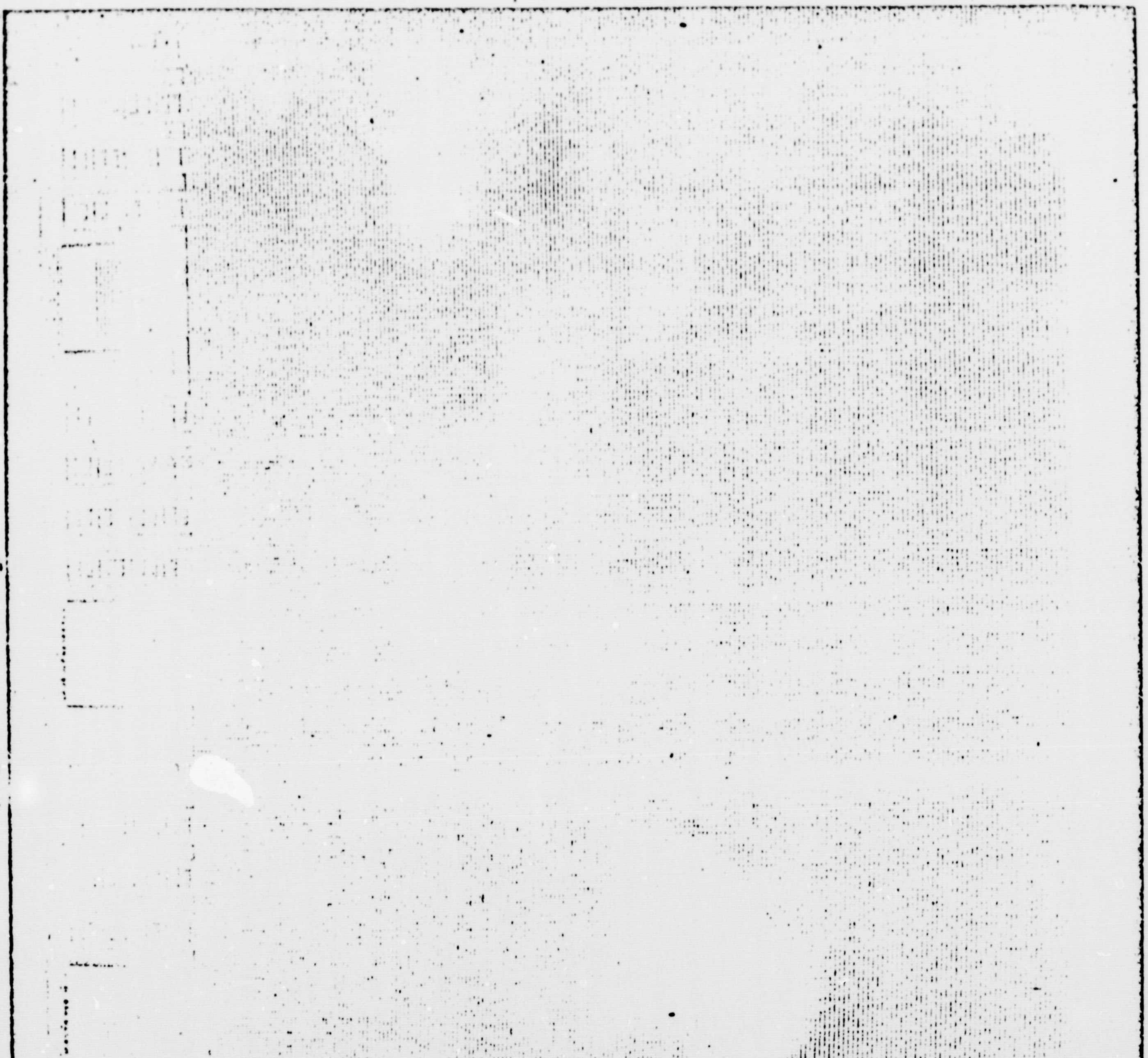


Figure 3

Figure 4

AUTHOR'S PROOF

DIGITAL VIDEOMAGNETOGRAMS IN REAL TIME

THOMAS J. JANSSENS and NEAL K. BAKER

The Aerospace Corporation, San Fernando Observatory, Los Angeles, California, U.S.A.

Abstract. The Aerospace – NASA Videomagnetograph began operation one month ago, two years after components were ordered and construction began. The design grew out of a desire to obtain magnetic fields in real time using an optical filter. The aim was to study and analyse magnetic configurations and changes, quantitatively if possible, with high spatial and temporal resolution and as much sensitivity as possible. This instrument is restricted to the line-of-sight component of the magnetic field and is primarily intended for high resolution studies of selected regions of the sun. The rationale behind our approach is shown in the next section and the design details in the following.

1. Analysis of An Idealized Magnetograph

In most solar magnetographs the measurement of the line-of-sight component requires the same processes, namely: light collection, spectral isolation, polarization selection, detection, subtraction, scanning, and data presentation.

The performance characteristics include the sensitivity, ΔB the area of a resolution element, a; the time resolution, T; and the number of resolution elements per scan, n. If we assume a given magnetic line and noise determined solely by the photon limit then we find that the product $n\,(\Delta B)^{-2}\,T^{-1}\,a^{-1}$ is invariant such that if n, T and a are changed, ΔB varies to hold the product constant. In theory this allows any desired trade off between spatial resolution, temporal resolution, and field of view but in practice such versatility is rather limited in actual magnetographs. Thus this product can perhaps be used then as a kind of performance figure of merit. It is proportional to the rate of photon detection and depends on the product εA (or $\varepsilon A N$ for a multichannel detector) where ε is the overall efficiency of the system, A is the area of the objective lens, and N is the effective number of data channels. The results are not surprising: that someone with an ideal detector would want a large aperture telescope, a high efficiency, and a multichannel detector.

Our approach has been to concentrate on increasing the effective number of parallel data channels, while using a rather small aperture. The number of data channels and mode of scanning are interrelated. Three types of scanning might be called a point-by-point scan, a slit scan, and a simultaneous exposure. In the point-by-point scan light from one element passes through a spectrograph and is analysed with the procedure repeated for each element in turn. This gives an effective $N=1$. In a slit scanning system such as the photographic subtraction technique developed by Leighton, photons along the exit slit of a spectroheliograph are simultaneously detected. This typically gives an effective N of 200 to 1000. The third method of simultaneous exposure requires the detection of photons from the entire image at once. This could have an effective $N=40000$ for a 200×200 array.

Simultaneous exposure requires use of a filter for spectral isolation rather than a spectrograph. This generally restricts one's versatility in the narrowness of the spec-

Symp. 43 - Howard

trum selected and the number of lines available for use, though filter technology has been steadily improving.

The two possible sensors for simultaneous exposure are film and video. With film one is restricted to a low duty cycle or a large expenditure of film. For example to take 0.2 S exposures each 10 S would decrease the effective N by a factor of 50 while to take exposures much more frequently would consume an enormous amount of film. In addition, photographic subtraction can be time consuming, difficult, and suitable from only single or double cancellation. Certainly photographic subtraction would not yield real time results.

A television camera is not without difficulties either. They usually cannot match film in resolution and signal-to-noise ratio at present. Also, the target of a video camera can hold only a given number of photoelectrons before being read off, so if one is to maximize the rate of photon detection the camera must be scanned at a fast rate, not operated in a slow scan mode. In a fast scan mode, the rates and capacity necessary to store and subtract video images in real time are quite a problem.

We decided to store, subtract, and average (enhance) the video images digitally rather than by analog means but found that the usual method of digitizing and storing the data for later analysis does not work because the video data is 4 million words per second, about 100 times faster than the usual magnetic tape recorder. A thousand reels of magnetic tape would be filled in only one hour at video rates.

Computing with the data is much faster than storing it but for our task the required speed and storage capacity would require a very large and expensive general purpose computer which was not available. To solve the problem we designed our own special purpose computer which would operate at these high video rates. The heart of the video computer is a high speed adder with a memory unit consisting of a digital magnetic disc which is used with sequential addressing instead of random accessing. The disc has 72 tracks, 130000 bits per track and rotates at 30 Hz. The advantages of a disc memory over core memory are, a much lower cost, a greater capacity, and higher access times. In addition, we can simultaneously use different parts of the disc for different tasks.

2. Description of the Videomagnetograph

The system shown in block diagram form in Figure 1 has four organization parts: (i) optical and video, (ii) data gathering and preprocessing section, (iii) display section, and (iv) analytic section.

The optical section consists of a telescope with a 15 cm diameter lens which forms a real image which is further enlarged onto the face of an SEC Vidicon. Spectral isolation of one wing of the 5324 Å line of Fe I is achieved by a hybrid filter with a bandpass of 0.11 Å similar to the filter developed by H. Ramsey of Lockheed. An electro optic crystal or a quarter wave plate is switched to alternately admit right and left handed circularly polarized light. One TV line is 1.5 arc sec and the field of view is 300 arc sec on a side.

The data gathering and preprocessing section includes the analog-to-digital converter, high speed adder, and 32 tracks of the disc divided into bands 1 and 2.

The incoming video signal is digitized into 8 bits (256 levels) by a 4 megacycle converter which is synchronized with the data flow of the disk. The output of the analog-to-digital converter can be added to or subtracted from a previously stored array in the data gathering area of the disk and then stored, thereby erasing the previous image array. This operation is controlled by the disk interface controller

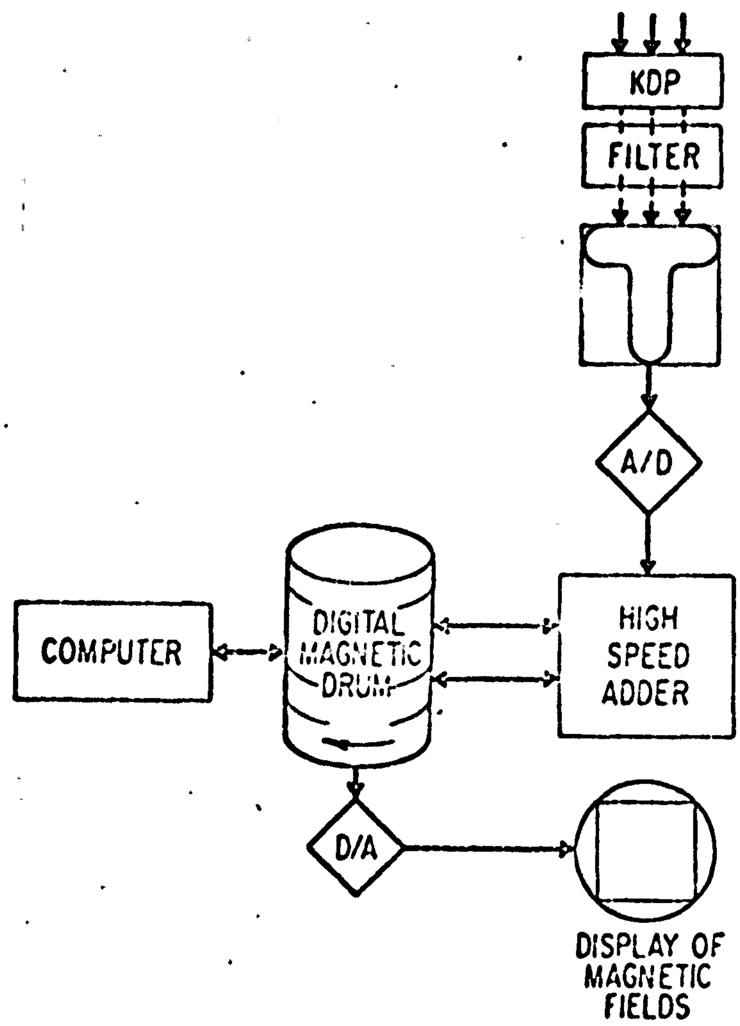


Fig. 1. Block diagram of the Aerospace – NASA Videomagnetograph.

which requires one instruction per frame whether to add or subtract the incoming image. It is operated on an interrupt basis by a small general purpose computer attached to the system.

After the completion of the data gathering mode, the system can be interrogated for information on the entire frame. At present, we can get the number of elements greater than a certain value, value of the *n*th largest element, and *m*th smallest element, or the average value. The position of the element can not be found in this interrogation mode.

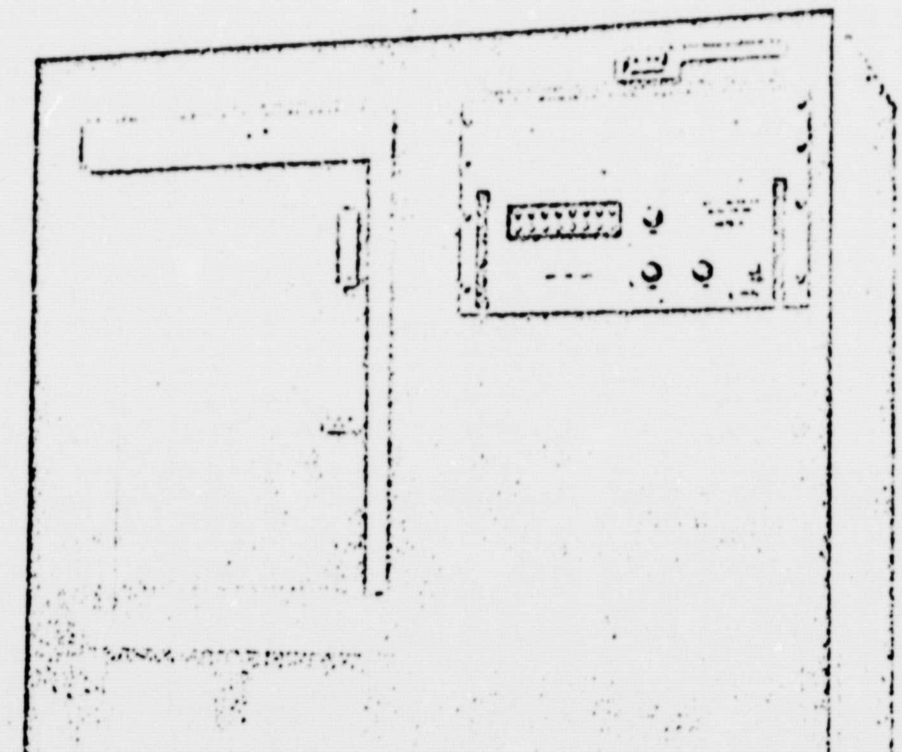


Fig. 2. Digital Processor for the Videomagnetograph.

For instance, the time to obtain the nth largest element in the array of 100000 points is 0.5 sec. This information is mainly used to set the levels for the display and to make distribution plots.

In the display section after a number of magnetic frames have been averaged to enhance sensitivity and achieve data compression, the results are displayed on a TV monitor for visual inspection and recording photographically. The magnetic field can be displayed with each brightness made to correspond to any desired magnetic strength in a number of ways, ranging from arbitrary selection of 8 to 16 gray levels to automatic selection by the computer. The display can be either in a positive or negative mode, logarithmic or linear scaling. This display data is transferred to the display section of the disk and displayed to the operator. The 4 bit (16 gray levels) data is

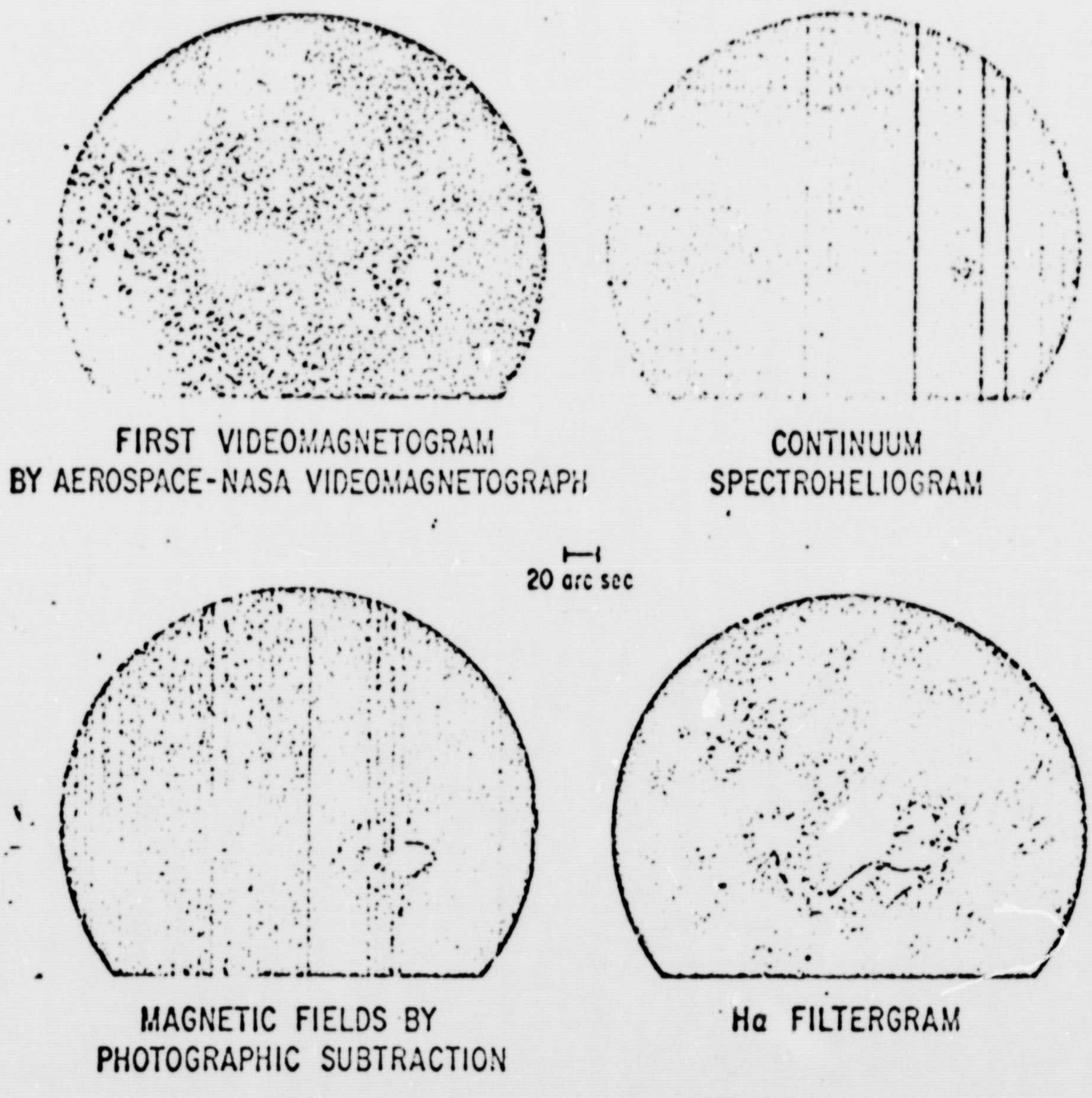


Fig. 3. First real time display of magnetic fields on July 17, 1970 at the Aerospace San Fernando Observatory. 40 sec were required for 500 subtractions. Other pictures are for comparison and confirmation.

connected to a digital-to-analog convertor and fed to two TV monitors which are synchronized to the disk. The operator can use a light pen on the monitor to select points or areas on which he wants more information, such as the numerical value of a specific point or position of the point. For areas, the operator can define rectangles or circles of various sizes in which he wants average values, maximum value, or minimum value.

Fig. 4. Videomagnetograms showing the development of an active region during three days from October 19 to 22, 1970. The numbers next to the density bars are not calibrated in Gauss.

The display section can also be used for graphic and alphanumeric display of the data, ranging from intensity plots on arbitrary cross sections of the picture, to distribution plots of the entire frame.

The analytic section consists of a Varian 620i computer and forty-eight tracks on the disc.

This data storage area is used as an intermediate storage to free the data gathering area. From this area, the data can be transferred to permanent storage on tape. It can also be used to hold image correction data which the computer could use to correct the raw data for imperfections or shading in the TV camera. The Varian computer controls the system and is available for further analysis of the data either in real time or later. The digital equipment is shown in Figure 2.

3. Results and Present Status

The initial results from the Videomagnetograph are shown in Figure 3. The videomagnetogram shown is a polaroid picture of the display monitor. Several days later the magnetic fields from photographic subtraction were available for confirmation of the fields and their polarities.

The initial result is very noisy. Later and somewhat less noisy magnetograms made later do not have matching photographic magnetograms for comparison. Improvements in the video preamplifier is expected to greatly improve the sensitivity but this and other improvements are not yet complete. The present effort is mostly directed toward greater reliability, higher sensitivity and calibration.

Acknowledgements

The authors wish to express their appreciation to E. B. Mayfield, G. A. Paulikas, and R. A. Becker of the Aerospace Corporation for their continued support of this project, to Greg Kozlowski of the Aerospace Corporation for technical support in all areas, to Donald Robbins of NASA MSFC for his continual collaboration, to Dave Rutland of Spatial Data for design and construction of the high speed digital electronics, to Dale Vrabec of the Aerospace Corporation for many helpful discussions, to Gary Chapman of the Aerospace Corporation for taking simultaneous photographic magnetograms and to Mary Gates of the Aerospace Corporation for her aid in assembly of reports.

Discussion

Deubner: What was the exposure time for the photographic magnetogram, as compared with that for the video-magnetogram taking 40 sec?

Janssens: The scan time for the photographic magnetic exposuro was two minutes.